Soil C and N changes under tillage and cropping systems in semi-arid Pacific Northwest agriculture

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Abstract

Soils in semi-arid regions are highly susceptible to soil organic matter (SOM) loss when cultivated because of erratic yield, removal of crop residue for feed or fuel, uncontrolled soil erosion, and frequent fallowing to increase water storage. It is important to quantify the effect of each factor to be able to identify agoecosystems that are sustainable and recognize the management practices that best sequester C in soil. We identified changes in SOM in long-term experiments, some dating from the early 1900s, by evaluating tillage and crop rotation effects at several locations in semi-arid regions of the US Pacific Northwest. The major factors influencing changes in organic C and N were the frequency of summer-fallow and the amount of C input by crop residue. Soil erosion was low in long-term studies, but even limited soil loss can have a substantial impact on C and N levels if allowed over many years. Yearly crop production is recommended because any cropping system that included summer-fallow lost SOM over time without large applications of manure. We conclude that most of the SOM loss was due to high biological oxidation and absence of C input during the fallow year rather than resulting from erosion. Decreasing tillage intensity reduced SOM loss, but the effect was not as dramatic as eliminating summer-fallow. Crop management practices such as N fertilization increased residue production and improved C and N levels in soil. SOM can be maintained or increased in most semi-arid soils if they are cropped every year, crop residues are returned to soil, and erosion is kept to a minimum. SOM loss may be more intense in the Pacific Northwest because fallowing keeps the soil moist during the summer months when it would normally be dry. Our experiments identify two primary deficiencies of long-term studies to measure C sequestering capability: (1) soil C loss can be partitioned between erosion and biological oxidation only by estimation, and (2) C changes occurring below 30 cm in grassland soils cannot be quantified in many instances because samples were not collected. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

An adequate amount of soil organic matter (SOM) is considered essential for long-term sustainable agriculture because declines generally decrease crop productivity (Allison, 1973). Changing SOM levels may alter the capacity for soil to act as a sink for atmospheric CO_2 and impact global climate change (Esser, 1990; Rounsevell and Loveland, 1994). Cropping intensity, tillage, residue input, and erosion all affect SOM. Both biological oxidation and soil erosion have

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a significant impact on soil C and N content (De Jong and Kachanoski, 1988), and can substantially alter SOM sequestering pathways.

Semi-arid lands are especially susceptible to deterioration in SOM because of inherent low production and erratic yield. Greater use of crop residue for feed or fuel contributes to accelerated SOM loss. Fallowing is practiced extensively to increase water storage and stabilize crop yield, but it accelerates C and N loss from soil (Campbell et al., 1990; Rasmussen and Collins, 1991). Recent studies in sub-humid and semi-arid soils indicate a strong positive relationship between the amount of C incorporated into soil and the organic C content of that soil (Larson et al., 1972; Havlin et al., 1990; Rasmussen and Collins, 1991; Paustian et al., 1992). But even though crop residues have a beneficial effect on SOM, rising human population in semi-arid regions increases the use of crop residues for animal food and fuel and thus reduces residue return to soil. Modern tractors and farm machinery permit more intensive tillage of soil, which further accelerates in organic C (Rasmussen and Collins, 1991). Cropping practices must be defined in terms of their effect on rate of change in soil C and N in order to develop future strategies for maintaining soil quality.

Long-term experiments (LTEs) are the primary sources of information to determine the effects of cropping systems, soil management, fertilizer use, and residue utilization on changes in soil C and N over time (Leigh and Johnston, 1994). They are usually the only source of information to verify the accuracy of models used to identify soil capacity to sequester C and mitigate global climate change (Powlson et al., 1996). Recently, there have been both national and international efforts to utilize long-term experiments to determine agricultural sustainability (Barnett et al., 1995), define land-use effects on SOM (Paul et al., 1997), and test models of soil C-sequestration (Powlson et al., 1996).

Oregon State University maintains several LTEs at the Columbia Basin Agricultural Research Center near Pendleton, OR. Other LTEs were conducted at Moscow, ID; Lind and Pullman, Washington; and Moro, OR, between 1915 and 1945. In this paper, we summarize some of the results that define tillage and rotation effects on long-term C and N changes in semi-arid soils of the Pacific Northwest. We also address some of the deficiencies arising from the use of LTEs to evaluate C sequestration in soil.

2. Materials and methods

2.1. Description of long-term experiments in the pacific northwest

Long-term research experiments were once located at Lind and Pullman in Washington, Moscow, ID, and Moro and Pendleton, OR. All have been terminated except for experiments at Pendleton. Research results from early long-term experiments conducted between 1920 to 1945 are included in this report to provide a perspective of early SOM change. Pendleton has six on-going long-term experiments, the earliest being established in 1931 and the latest in 1981 (Table 1).

Climatic, geographical and soil data for Pacific Northwest sites in relation to that in the Great Plains are shown in Table 2. Precipitation distribution in the Pacific Northwest is distinctly different from that in the Great Plains or Canadian Prairies. Climate in the

Table 1
Description of the on-going long-term tillage and rotation experiments at Pendleton, OR

Year initiated	Experiment name	Crop rotation	Variables
1931	Grass pasture (GP)	Grassland	None
1931	Continuous cereal (CC)	Cereal/cereal	None
1931	Crop residue management (CR)	Wheat/fallow	Nitrogen, manure, burning, pea vines
1940	Tillage fertility (TF)	Wheat/fallow	Tillage, nitrogen
1963	Wheat/pea (WP)	Wheat/legume	Tillage
1982	No-till wheat (SF)	Wheat/wheat[a]	Nitrogen

[a] Converted to wheat/fallow in 1991.

Table 2
Climatic, geographic and soil data for Pacific Northwest sites in relation to that for a typical Great Plains site, Akron, CO

Characteristic	Lind	Moro	Pendleton	Pullman	Moscow
Annual precipitation (mm)	243	286	415	546	583
Annual temperature (°C)	9.89	9.44	10.21	8.30	8.45
Pan evaporation (mm)[a]	1379	b	1361	b	1041
Summer precipitation (%)[c]	31	29	32	29	b
Station designation	Lind3NE	Moro	PBES	Pull2NW	U of I
Reporting period	1931–94	1928–94	1956–94	1940–94	1903–94
Longitude (deg, min, N)	47:00	45:29	45:43	46:46	46:44
Latitude (deg, min, W)	118:35	120:43	118:38	117:12	116:58
Elevation (m)	497	570	454	777	811
Soil series	Ritzville		Walla Walla		Palouse
Soil classification (USDA)	Calciorthidic haploxeroll		Typic haploxeroll		Pachic ultic haploxeroll

[a] Seven month period (1 April–31 October).
[b] Not available.
[c] Five month period (1 April–31 August).

Pacific Northwest is characterized by cool wet winters and hot dry summers. Climate at the Pendleton site is generally representative of average conditions in the semi-arid Pacific Northwest, with mean annual precipitation of 415 mm located between the extremes of 243 and 583. Total precipitation for Pendleton is quite similar to that for Akron, Colorado in the Great Plains (415 vs. 419 mm), but the distribution patterns are distinctly different. Only 32% of total precipitation at Pendleton is received during the summer growing season (1 April–31 August), in contrast to 72% at Akron. Inadequate summer rainfall at Pendleton severely restricts yield of warm-season crops, but high winter rainfall enhances the performance of cool-season winter annuals.

Soils in the Pacific Northwest are mainly loess-derived medium-textured silt loams of young geological origin. Landscapes are complex, gently to steeply sloping, and highly susceptible to wind and water erosion when not protected by adequate crop cover. Present land use includes alternating wheat (*Triticum aestivum* L.)/fallow (fallow one year in two) where precipitation is less than 375 mm per year, fallow frequency of one year in 2–5 years in the 375–450 mm zone, and annual crop production(no fallow) where precipitation exceeds 450 mm.

The LTEs at Pendleton include studies in wheat/fallow (W/F), wheat/pea (*Pisum sativum* L.)(W/P),

and annual wheat (W/W) cropping (Rasmussen and Smiley, 1997). Tillage comparisons are a part of the W/F and W/P experiments. A long-term grass pasture (GP) is maintained to provide a grassland ecosystem for use as a reference for comparing the effects of cultivated agriculture on soil quality. The W/F and W/P experiments have four replicates, while the W/W and GP experiments are large unreplicated blocks.

Crop rotation studies were conducted at Moscow, Pullman, Pendleton, and Moro from the early 1910s until the early 1950s (Horner et al., 1960). Rotation studies compared annual wheat with various frequency of fallowing and often included inorganic fertilizer and manure addition treatments. Records of plot size and replication are not available for many of the studies. A replicated straw loading rate study was conducted at Lind from 1922 to 1940 that included 0, 0.89, 1.78, and 3.56 Mg ha^{-1} applied every second year during the fallow period of a W/F rotation (Smith et al., 1946).

2.2. Chemical analysis and analytical methods

Soil samples have been collected about every 11 years from the Crop Residue Management study at Pendleton (Rasmussen and Parton, 1994), and periodically from the other experiments (Rasmussen and Rohde, 1988; Rasmussen and Collins, 1991). Sam-

pling depth was 0–30 and 30–60 cm. Bulk density of the 0–30 cm zone was determined at several locations on the station in 1931. Soil samples were collected from the 0–20 cm depth for all LTEs in 1990, with selective sampling from 20–40 and 40–60 cm depths to establish C change with depth. Soil samples consisted of a composite of 12 to 16, 1.6 cm diameter cores from each treatment replicate or designated area of the experiment. Samples were uniformly mixed and triplicate subsamples removed for chemical analysis, resulting in 12 analytical values per treatment. Bulk density was also determined in 1991 for most experiments.

Pendleton soil samples were analyzed for total N by macro-Kjeldahl procedures in 1931, 1941 and 1951; micro-Kjeldahl in 1964; Al-block tube digestion in 1976 and automated dry combustion in 1976 and 1986. Correlation between analytical methods was performed when possible because soil samples collected before 1976 were not saved.

The 1931–1951 Pendleton samples were analyzed for SOM by a loss-on-ignition method (Rather, 1917). Individual sample results showed high variability but means appeared reasonably accurate (Rasmussen and Parton, 1994). The SOM values were converted to C by multiplying by the 'generally accepted' value of 0.58 (Nelson and Sommers, 1982). Rather (1917) reported a conversion ratio of 0.60 in his SOM study. Samples collected since 1976 have been analyzed for organic C by dry combustion and a CO_2 analyzer. Carbon content was calculated from concentration and bulk density values.

Soil samples were collected at the beginning and end of the experiments at Pullman, Moscow, Moro, and Lind. Sampling depth was up 15 or 30 cm, but sampling procedures were not reported. Soils were analyzed for C by standard Association of Official Agricultural Chemists methods existing at the time of sampling (AOAC, 1935). Sampling intensity and bulk density were not reported for the studies. A bulk density of 1.30 Mg m^{-3} was assumed for the 0–30 cm layer of Palouse soil at Moscow, based on research by Hammel (1989). A value of 1.25 was assigned to the 0–30 cm layer of the Ritzville soil, based on bulk densities of 1.15 in the plow layer and 1.34 in the subsoil reported by Gilkeson (1965). Soils at all locations have essentially no inorganic C in the upper 30 cm of soil.

Table 3
Soil C and N change in early long-term experiments in the Pacific Northwest

Location	Period covered	Crop rotation [a]	Initial C content (g kg^{-1})	Straw residue treatment			
				Removed	Retained	Nitrogen added[b]	Manure added[c]
				C change, (kg ha^{-1} yr^{-1})			
Moro	1932–42	W/F	10.1	−261	−282	d	+43
Pendleton	1931–64	W/F	13.6	−188	−188	−141	+25
Pullman	1921–52	W/F	16.5	−337	−373	−122	−22
Pullman	1921–52	W/W	17.2	−72	−100	+337	+409
Moscow	1923–45	W/O/F	19.6	−679	d	d	−150
Moscow	1923–45	W/W	20.4	−309	d	d	+509
				N change, (kg ha^{-1} yr^{-1})			
Moro	1932–42	W/F	10.1	−30	−22	d	−7
Pendleton	1931–64	W/F	13.6	−17	−12	−8	+11
Pullman	1921–52	W/F	16.5	−42	−35	−21	−17
Pullman	1921–52	W/W	17.2	−19	−20	+9	+19

[a] WF = Wheat/fallow; WW = Wheat/wheat; WOF = Wheat/oats (Avena sp.)/fallow.
[b] Nitrogen applied at rates equivalent to 17, 32, and 15 kg ha^{-1} yr^{-1} at Pendleton, Pullman, and Moscow, respectively; straw retained.
[c] Manure applied at rates equivalent to 11.2, 11.2, 6.7 and 11.2 t ha^{-1} yr^{-1} at Moro, Pendleton, Pullman and Moscow, respectively; straw retained.
[d] Not applicable.

3. Results and discussion

3.1. Factors affecting organic C and N in soil

3.1.1. Crop rotation

Early studies show that soil C and N loss was always greater when crop rotations included fallow (Table 3). Average C loss was much greater at Pullman and Moscow than at Pendleton. Soils at the Pullman and Moscow sites have higher SOM, however, and the rate of SOM loss is linearly correlated with the amount initially present (Fig. 1). It appears difficult to prevent C loss from high SOM soils during the early years under cultivation when crop rotation includes fallow. High biological oxidation when soils are fallowed usually dominates erosion as the major cause for C loss during the early years of cultivation (Gregorich and Anderson, 1985). There are no actual measurements of erosion in our long-term experiments, so we cannot partition changes between biological oxidation and erosion. Horner et al. (1960) reported erosion rates of 5–10 Mg ha^{-1} yr^{-1} and 1–2 Mg ha^{-1} yr^{-1} for W/F and W/W rotations, respctively, at Pullman, WA.

Estimated yearly erosion for the wheat/fallow study at Pendleton is less than 2 Mg ha^{-1} using the RUSLE soil loss equation (Duff et al., 1995). General estimates of annual C input can be calculated from yield and harvest index for the varieties grown. Differences in C input at Moscow between the W/W and W/O/F rotations (1030 vs. 900 kg ha^{-1} yr^{-1}) do not account for differences in C loss.

3.1.2. Manure and N fertilizer addition

Addition of manure or N fertilizer decreased C and N loss from soil, with greater conservation found in annual-crop systems (Table 3). Soil organic C and N tended to increase at all locations with annual cropping plus manure application. Manure had a greater effect than that of N fertilization, but manure also supplies C and can increase total C input by 30–80%. Manure application is the only treatment at Pendleton that has maintained soil organic C at equilibrium in a W/F rotation (Rasmussen and Parton, 1994). Manure additions were 33 Mg ha^{-1} every third year at Moscow and 22 Mg ha^{-1} every second year at Pendleton, and probably supplied adequate to excess N for all
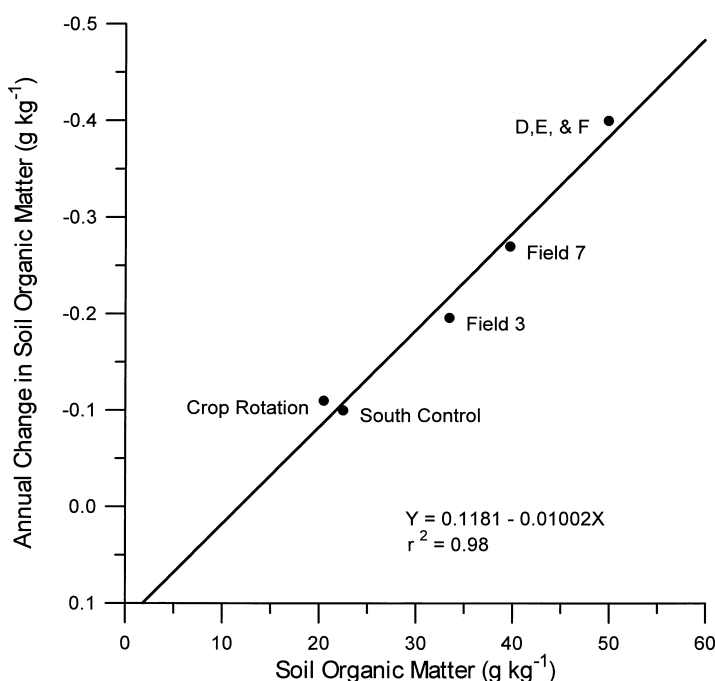

Fig. 1. Relationship of the rate of change in soil organic matter to its original concentration during the early years of cultivation. 0–15 cm soil depth; Pullman, WA. (adapted from Horner et al., 1960).

crops grown. Unfortunately, C and N content of manure was not determined in early studies. Carbon input from manure can be highly variable, depending on type, moisture content and method of application (Rasmussen and Collins, 1991). The C and N input from the manure at Pendleton averages 1730 and 145 kg ha^{-1} per crop, respectively. Carbon input from crop residue can be estimated with reasonable accuracy, but the same is not true for manure.

3.1.3. Crop residue return to soil

Studies at both Lind and Pendleton show linear changes in organic C with increasing residue addition to soil (Rasmussen and Albrecht, 1998). About 18% of added C was incorporated into the organic C fraction of soil. Retention efficiency appears slightly higher than in Canadian prairie soils (Campbell et al., 1991) and Iowa corn (*Zea mays* L.) belt soils (Larson et al., 1972). Substantially less C input was required at the more arid Lind site (33 kg ha^{-1} yr^{-1}) than at Pendleton (437 kg ha^{-1} yr^{-1}) to maintain organic C in the 0–30 cm zone at the steady state. The C requirement for Lind appears quite low, however, and may not be valid because analytical procedures used for SOM in the 1915 and 1940 samples may not have produced equivalent values. The rate of C retention in SOM as a function to C input, however, should not be affected by the deficiencies in analytical methods.

In general, less C was lost from soil at Pendleton when cropped every year than when cropped in W/F rotation (Table 4). All W/F systems showed negative C trends, suggesting deteriorating soil quality. Main-taining SOM at the steady state in rotations that include fallow appears nearly impossible when soils are moldboard plowed. Adoption of conservation tillage may be the only way to produce a condition where soil C is aggrading. Increasing crop yield through improved technology would appear beneficial as long as residues are returned to the soil.

Change in N concentration over time was less negative than was C change (Table 4). Differences are not unexpected since all systems received N fertilization. Only the fallow systems showed negative N change. Nitrogen retention increased substantially with a reduction in tillage intensity.

A continuing decline in C and N in the 30–60 cm zone in the wheat/fallow study at Pendleton indicates long-term shifts that have not reached the steady state (Fig. 2). The decline is not related to residue management or level of C or N input (Rasmussen and Parton, 1994). This implies that yearly biological oxidation loss of C exceeds the C input from cereal roots, in contrast to the steady state that existed under annual grassland.

3.1.4. Tillage

Converting from plowing to mulch (non-inversion) tillage at Pendleton conserved C and N in both wheat/fallow rotation and annual cropping, with higher concentration found under annual cropping (Table 4). Preliminary interpolations indicate no-till cropping can achieve an aggrading C system in annual cropping and is perhaps the only tillage system with a chance to maintain SOM at the steady state in rotations with

Table 4
Effect of cropping system (rotation and tillage) on long-term C and N change in soil at Pendleton, OR during 1931–1991. Soil depth 0–20 cm

Rotation (tillage)[a]	Years conducted	Actual C change	Estimated 60-year C change	Actual N change	Estimated 60-year N change
		(g kg^{-1})			
W/F (moldboard plow)	60	−3.55	−3.55	−0.216	−0.216
W/F moldboard plow)	40	−2.30	−3.45	−0.117	−0.176
W/F (stubble mulch)	40	−1.88	−2.79	−0.051	−0.077
W/P (moldboard plow)	28	−1.25	−2.69	+0.032	+0.069
W/P (minimum till)	28	+0.04	+0.09	+0.103	+0.221
W/W (moldboard plow)	60	−0.99	−0.99	+0.051	+0.051
W/W (no till)	10	+0.10	+0.60	+0.029	+0.174
Grass pasture[b]	60	+3.38	+3.38	+0.585	+0.585

[a] WF = Wheat/fallow, WP = Wheat/pea, WW = Wheat/wheat.
[b] Grass pasture consists of introduced grasses with limited grazing, occasional reseeding and infrequent fertilization.
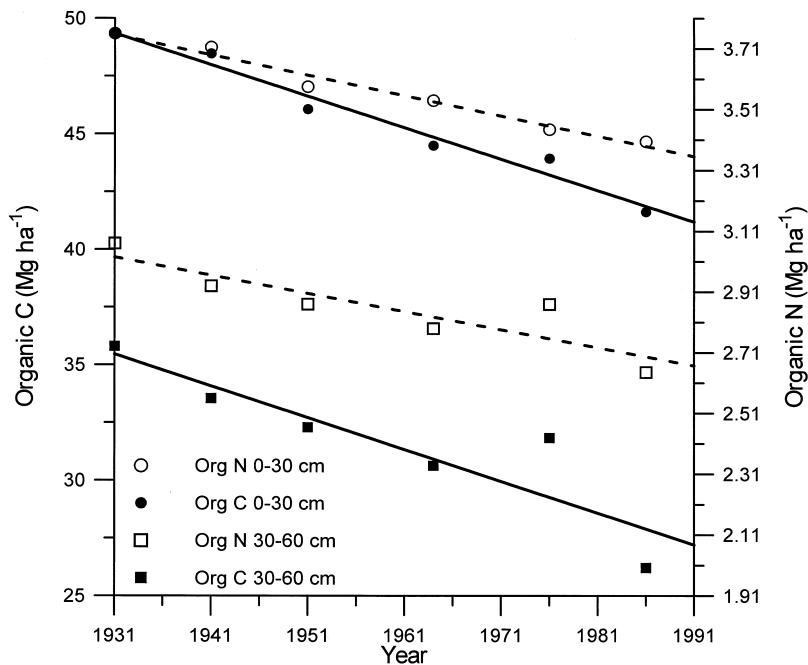
Fig. 2. Change in the mass (Mg ha^{-1}) of soil C and N in the 0–30 cm and 30–60 cm soil depths between 1931 and 1986 for a wheat/fallow experiment at Pendleton, Oregon (adapted from Rasmussen and Parton, 1994).

50% fallow. The no-till experiment has not been in place long enough to be sure that the present trend is accurate. All studies at Pendleton are located on nearly-level ground (<2% slope), and wind and water erosion are minimal. On landscapes where soil erosion consistently exceeds acceptable limits, steady-state conditions would be much more difficult to achieve.

3.1.5. Cropland/grassland conversion

The top 30 cm of soil at Pendleton lost about 35% of its C content in the first 50 years that it was farmed (1881 to 1931). Since conversion from cropland back to pasture in 1931, both soil C and N have increased substantially, though not at the same rate (Table 4). The soil, some 60 years after being seeded back to grass, has regained about half of the C lost through 50 years of cultivation. Carbon content data indicate that at least 120 years are required to return SOM to pre-cultivation levels (Rasmussen and Albrecht, 1998). Change is slow, which implies that dramatic increases in SOM should not be expected from a 10 year cropland retirement systems such as the USDA Conservation Reserve Program.

4. Summary of pacific northwest research

4.1. Major factors controlling C and N change in soil

The major factors affecting organic C and N in semi-arid soils are the frequency of summer-fallow in crop rotations and the level of C input into soil through crop residue and added amendments. Trends for the Pacific Northwest agree very closely with those found for Canadian prairie soils (Campbell et al., 1990). Fallowing intensifies C loss from soil throughout the area, with indications that SOM cannot be maintained in rotations that include both fallow and conventional tillage. Decreasing tillage intensity reduces SOM decline, but the effect is not as dramatic as eliminating fallow. The detrimental effect of fallowing is two-fold. Summer-fallow systems produce no residue during the fallow year since they are kept weed- and crop-free, and biological oxidation is probably greater than in cropped soil.

Summer fallowing may be more detrimental to SOM retention in the Pacific Northwest than in the Great Plains because of the difference in rainfall

patterns. The Pacific Northwest receives low summer rainfall and soils are essentially dry for more than 90 days every summer, which tends to reduce biological oxidation potential. However, weed-free summer fallow allows soil to remain moist during the summer instead of drying out, which permits much greater biological oxidation than would normally occur. The Great Plains soils, in contrast, normally remain moist every year because of high summer rainfall and fallowing has limited influence on biological oxidation. Theoretically, summer fallowing in winter rainfall climates should be more detrimental to SOM than fallowing in summer rainfall climates.

Increasing residue return to soil has been shown to increase soil organic C linearly, with approximately 18% of all residue C incorporated into SOM (Rasmussen and Collins, 1991; Rasmussen and Albrecht, 1998). Carbon input necessary to maintain SOM in soil at the steady state appears to increase with increasing precipitation. While wheat yield has increased 2–3 fold over the past 60 years, C input from cereal residues has not been so dramatic because of the progressive decrease in straw/grain ratio associated with semi-dwarfing of wheat (Rasmussen and Parton, 1994). Total residue production per hectare has increased only 20–30%, much less than residue increases associated with corn grain yield increases in the central US.

4.2. Deficiencies in long-term experimental data

Several deficiencies arise when using LTE data experiments to project C and N storage in agricultural soils. It is difficult to separate C and N losses due to soil erosion from those due to biological oxidation of SOM. Actual erosion measurements have seldom been made on LTEs because of the potential physical damage in setting up measuring instruments on relatively small plots. Annual erosion rates are presumably much higher when fallow is included in crop rotation, and erosion loss can comprise a substantial portion of long-term C change in prairie soils (De Jong and Kachanoski, 1988). Soil C loss from erosion has been projected to be greater than C loss from biological oxidation loss after 30–50 years of cultivation (Gregorich and Anderson, 1985). Losses have generally been calculated using models such as RUSLE or EPIC, or predicted from ^{137}Cs change. Model results

appear to be compatible with visual estimates, but we have no experimental data to validate this conclusion.

Carbon loss through biological oxidation needs to be identified in relation to loss through soil erosion, since the fate of C is quite different. Oxidized C is presumably emitted to the atmosphere as CO_2 while eroded C may be transported and buried at depths where decomposition and C turnover is much slower. Biological oxidation can represent a substantial portion of the C loss in semi-arid areas where land lies fallow for 6–15 months in a 2-year period. Fallowing increases soil moisture during summer which accelerates residue decomposition. Coupled with little or no residue return to soil, biological oxidation can deplete SOM much more rapidly than in annually-cropped soil. Rasmussen and Albrecht (1998) illustrated this dilemma with data from Pendleton. Carbon losses over time in a wheat/fallow rotation were much greater than could be accounted for by the calculated erosion rates. Thus, biological oxidation must be considered the dominant pathway of C loss even though its contribution has not been directly measured.

Modeling of C and N change in grassland soils also appears to require an estimate of losses or gains below a soil depth of 30 cm. Native grasslands had considerably greater root mass than most cultivated crops. Lower root production by cultivated crops, especially where fallowing occurs, probably lowers C input into the subsoil compared to native grassland conditions. Few LTEs have measured SOM below 30 cm, and do not address C or N changes at deeper depths. Changes in soil C below 30 cm may be a substantial source of CO_2 emission when modeling C-sequestering capability of soils, and N movement below the root zone.

An additional limitation of LTEs are erosion rates that are less than those on surrounding landscape. LTEs are generally located on the most gently sloping fertile lands and have low erosion rates. Trends in SOM change obtained on gently sloping soils must then be transferred to steeper landscape positions with less-fertile soil. We know essentially nothing about the validity of this data transfer.

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